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REGULAR ARTICLE

Effects of soil acidity and water stress on corn and soybean performance under a no-till system

Helio Antonio Wood Joris · Eduardo Fávero Caires ·
Angelo Rafael Bini · Danilo Augusto Scharr ·
Adriano Haliski

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Abstract

Background and Aims Field studies have demonstrated that aluminum (Al) toxicity is low in no-till systems during cropping seasons that have adequate and well-distributed rainfall. This study evaluated the performance of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merrill) on an acid loamy soil under a long-term no-till system, in response to surface liming and as affected by genotypic tolerance to Al and water stress.

Methods A field trial examined the effect of surface application of lime (0, 4, 8, and 12 Mg ha^{-1}) on no-till corn and soybean nutrition and yield. Trials were also carried out in undisturbed soil columns taken from the unlimed and limed plots. Two hybrids/cultivars of corn and soybean, one sensitive and the other moderately sensitive to Al were grown at two soil moisture levels with and without water stress (50 % and 80 % water filled pore space).

Results Alleviating soil acidity by liming improved nutrition and increased grain yields of corn and soybean. The benefits of liming on root length density, nutrient uptake and shoot biomass production of corn and soybean were more pronounced in Al-sensitive genotypes under water stress.

Conclusions The results suggest that plants exposed to drought stress under no-till systems are more affected by Al toxicity.

Keywords Dolomitic lime · Surface application · Drought stress · Aluminum toxicity · Calcium · Root length

Introduction

In many areas of the world, soil acidity limits agricultural yield. The low content of base cations, especially calcium (Ca), and aluminum (Al) toxicity affect root growth and the absorption of water and nutrients by plants, usually causing a reduction in crop yields on acid soils (Sumner et al. 1986; Marsh and Grove 1992; Tang et al. 2003).

In tropical and subtropical regions, no-till systems with a diversified crop rotation have proved to represent one of the most effective strategies to improve the sustainability of agriculture, contributing to minimize soil and nutrient losses by erosion. No-till systems worldwide are estimated to cover over 105 million hectares (Mha) (Derpsch and Friedrich 2009). The

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H. A. W. Joris
Instituto Agronômico de Campinas (IAC),
Av. Barão de Itapura, 1481,
Campinas 13012-970 São Paulo, Brazil

E. F. Caires (✉) · A. R. Bini · D. A. Scharr · A. Haliski
Department of Soil Science and Agricultural Engineering,
Universidade Estadual de Ponta Grossa (UEPG),
Av. Gen. Carlos Cavalvanti, 4748,
Ponta Grossa 84030-900 Paraná, Brazil
e-mail: efcaires@uepg.br

area under no-till has grown especially rapidly in South America, where some countries such as Argentina, Brazil, Paraguay and Uruguay are applying this system on approximately 70 % of the total cultivated area (Derpsch and Friedrich 2009). In Brazil, the cultivated area under no-till has rapidly grown to its current size of 25.5 Mha (Derpsch and Friedrich 2009).

In order to control soil acidity in no-till systems, lime is applied on the surface without incorporation. Surface liming improves topsoil acidity on the relatively short term, whereas subsoil acidity is generally improved much more slowly, particularly in soils with variable charge (Ernani et al. 2004). Field studies have shown that the movement of lime to depth varies according to the timing and the rates of liming, soil type, weather conditions, management of acidic fertilizers and cropping systems (Moschler et al. 1973; Blevins et al. 1978; Oliveira and Pavan 1996; Gascho and Parker 2001; Conyers et al. 2003; Caires et al. 2005).

No-till systems affect some chemical characteristics related to soil acidity, which may influence plant development. Crop residues left on the soil surface to serve as a mulch (Miyazawa et al. 1993; Franchini et al. 2003) and a higher organic matter content at the soil surface (Blevins et al. 1978; Bayer et al. 2000; Rhoton 2000) may reduce Al toxicity (Brown et al. 2008; Vieira et al. 2008; Alleoni et al. 2010). The rise in soil cation exchange capacity, caused by a higher content of organic matter can provide sufficient concentrations of exchangeable Ca and Mg, even in highly acidic soils (Caires et al. 1998; 2006). Calcium mitigates the toxic effects of Al on root growth (Alva et al. 1986; Brady et al. 1993). In addition, soil cover reduces water loss by evaporation and provides more available moisture in the surface layers (Salton and Mielniczuk 1995; Tarkalson et al. 2006; Moussa-Machraoui et al. 2010), which may promote nutrient uptake under adverse acidic soil conditions (Caires and Da Fonseca 2000). Field studies have shown that high crop yields can be obtained on acid soils under no-till (Tissi et al. 2004; Caires et al. 2005; 2006), but the reasons for this remain unclear. Caires et al. (2008a) evaluated the effects of surface liming on no-till corn, soybean, and wheat yield and root growth, and found that only the wheat crop showed a positive response to lime application. This was attributed to water stress during wheat development, whereas soybean and corn did not suffer water limitations during their growth cycles. Since wheat cultivars are more tolerant to soil acidity than soybean cultivars (Muzilli et al. 1978) and because corn plants are more sensitive to acidity when there is less moisture in the soil (Freire 1984), the productivity of soybean and corn would also likely have been impacted by soil acidity if water stress had occurred during their development (Caires et al. 2008a). However, there is a lack of information on the effects of soil acidity and water stress on corn and soybean productivity under no-till systems.

This study reports on a trial that examined corn and soybean performance on an acid loamy soil under a long-term no-till system, in response to surface application of lime and as affected by genotypic tolerance to Al and water stress. Our objectives were (i) to evaluate the effect of surface application of lime on nutrition and yield of corn and soybean crops, in a long-term no-till system and (ii) to examine the influence of soil acidity and water stress on shoot biomass production, root length density, and nutrient uptake of two hybrids/cultivars of corn and soybean, one sensitive and the other moderately sensitive to Al. Both types of hybrids/cultivars were grown at two soil moisture levels, with and without water stress, in undisturbed soil columns taken from unlimed and limed field plots. We hypothesized that corn and soybean plants exposed to drought stress under no-till systems are more affected by Al toxicity, and that the effects of soil acidity reduction by surface liming on no-till corn and soybean growth and nutrition are greater when water in the topsoil is depleted.

Materials and methods

The study was carried out in a long-term no-till system, 52 months after surface application of lime at different rates. Undisturbed soil columns were taken from the field plots to perform an experiment in the greenhouse, in order to simulate different levels of water availability.

Field experiment

The experiment was performed in Ponta Grossa, PR, Brazil (25°07′50″S, 50°15′13″W), on an Oxisol (loamy, kaolinitic, thermic Typic Hapludox). Before the establishment of the experiment, in May 2004, soil chemical and particle-size distribution analyses of the 0–20 cm depth showed the following results: pH 4.1 (1:2.5 soil: 0.01*M* $CaCl_2$ suspension); exchangeable Al, Ca, Mg, and K contents of 12, 5, 5 and 1.7 $mmol_c$ L^{-1}, respectively; total acidity at pH 7.0 (H+Al) of 110 $mmol_c$ L^{-1}; P (Mehlich-1) 6.0 mg L^{-1}; total organic matter 31.1 gL^{-1}; base saturation 9.6 %; clay, silt and sand at 295, 240, and 465 gkg^{-1}, respectively. Considering the clay fraction, the soil had 265.8 gkg^{-1} of kaolinite, 26.8 gkg^{-1} goethite, and 2.4 gkg^{-1} hematite. At the beginning of the experiment, the field site had been used for grain cropping under the no-till system for 26 years.

A randomized complete block design was used and four treatments were replicated three times. Plot size was 6.5 m×6.4 m. Treatments consisted of dolomitic lime broadcast on the soil surface at the rates of 0, 4, 8, and 12 Mg ha^{-1} in May 2004. The lime rates were calculated to raise base saturation in the topsoil (0–20 cm) to 40, 65, and 90 %, respectively. The dolomitic lime used contained 221 gkg^{-1} Ca, 140 g kg^{-1} Mg, and 85 % effective calcium carbonate equivalent. From grain size analysis, 557, 290, and 153 g kg^{-1} of particles passed through 0.30, 0.84, and 2 mm sieves, respectively.

The no-till system involved no disturbance to the soil except the sowing operation. The sequence of crops from 2004 to 2008 was as follows: black oat (*Avena strigosa* Schreb) in 2004, corn (*Zea mays* L.) in 2004–2005, black oat in 2005, soybean (*Glycine max* L. Merrill) in 2005–2006, black oat in 2006, soybean in 2006–2007, black oat in 2007, soybean in 2007–2008, and black oat in 2008. Black oat was grown as a cover crop, and crop residues were left on the soil surface following grain harvest of corn and soybean.

Corn hybrid P 30 F53, was sown in early spring in 2008 (September) at a seeding rate of 6 seeds m^{-1}, with row spacing of 0.90 m. Soybean cv. CD 206 inoculated with *Bradyrhizobium japonicum* was sown in the spring in 2009 (October) at a seeding rate of 15 seeds m^{-1} and row spacing of 0.45 m. Fertilizer rates varied with crops, according to soil test recommendations for Parana State. For the corn crop, fertilizers were applied at rates of 130 kg Nha^{-1}, 38 kg P ha^{-1}, and 80 kg Kha^{-1}. Soybean received fertilizers at rates of 5 kg Nha^{-1}, 22 kg P ha^{-1}, and 20 kg Kha^{-1}. The corn and soybean genotypes used are moderately sensitive to Al toxicity.

Rainfall and air temperature data for the study period are shown in Fig. 1. Throughout the spring-summer season (corn in 2008–2009 and soybean in 2009–2010) while crops were growing, air temperatures were normal and there was no water limitation. Lower rainfall rates were recorded only for a short period during the early development of corn in 2008.

Leaf samples of corn (2008–2009) and soybean (2009–2010) included 30 leaves per plot, collected during the flowering period of the crops according to the procedures described by Malavolta et al. (1997). The samples were washed in de-ionized water, dried in a forced-air oven at 60 °C until a constant weight was achieved, and subsequently ground. Leaf tissue analysis was performed using sulfuric acid digestion for N and nitric-perchloric acid digestion for P, K, Ca, Mg, S, Cu, Zn, and Mn (Malavolta et al. 1997). Nutrient contents were determined using the Kjeldahl method for N, metavanadate colorimetry for P, flame photometry for

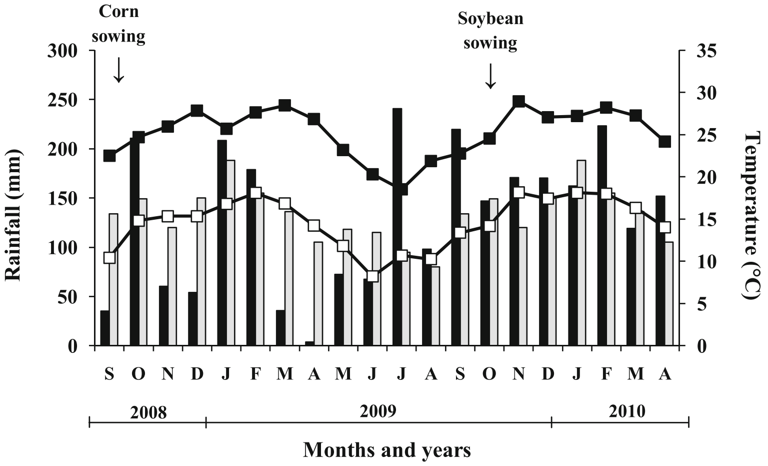

Fig. 1 Monthly rainfall (*black areas*), and maximum (*closed square*) and minimum (*open square*) temperatures during the growing season of the crops (2008–2010), and 45 years average monthly rainfall (*shaded areas*) at Ponta Grossa, Southern Brazil

K, $BaSO_4$ turbidimetry for S, and atomic absorption spectrophotometry for Ca, Mg, Cu, Zn, and Mn. Corn and soybean were harvested from 10 m^2 areas in February 2009 and March 2010, respectively. Grain yield was expressed at 130 gkg^{-1} moisture content.

Soil samples were taken from each plot at depths of 0–5, 5–10, and 10–20 cm. Twelve soil cores were taken in each plot using a soil probe sampler to obtain a composite sample. The samples were taken in September 2008, before sowing corn, 52 months after lime application. Soil pH was determined in a 0.01 M $CaCl_2$ suspension (1:2.5 soil:solution, v:v). Total acidity at pH 7.0 (H+Al) was determined using the SMP buffer procedure described by Pavan et al. (1992). Exchangeable Al, Ca, and Mg were extracted with neutral 1 M KCl, according to standard methods used by the Agronomic Institute of the Parana State (Pavan et al. 1992). Soil Mn was extracted with DTPA-TEA (0.005 M diethylenetriaminepentaacetic acid+0.1 M triethanolamine+0.01 M $CaCl_2$) solution at pH 7.3, as described by Lindsay and Norvell (1978). Exchangeable Al (KCl – exchangeable acidity) was determined by titration with 0.025 M NaOH; Ca and Mg by titrating with 0.025 M EDTA; K by flame photometry; and Mn by atomic absorption spectrophotometry. The effective cation exchange capacity (ECEC) was calculated by summation of exchangeable cations (Al+Ca+Mg+K), and Al saturation as: Al saturation=100 (Al/ECEC). The cation exchange capacity (CEC) at pH 7.0 was calculated by summation of basic cations and total acidity at pH 7.0 [Ca+Mg+K+(H+Al)], and the base saturation (V) as: V=100 (Ca+Mg+K/CEC).

Data from the chemical analysis of soil, leaf, and crop grain yields were submitted to an analysis of variance and simple regression using a randomized complete block design in SAEG software (Ribeiro Júnior 2001). The model was established based on the magnitude of the determination coefficients significant at $P<0.05$.

Greenhouse experiment

Before sowing corn in 2008 and soybean in 2009, four undisturbed soil columns were taken from each experimental plot, i.e. in all lime application rates (0, 4, 8, and 12 Mg ha^{-1}) and replicates. Columns were taken using polyvinyl chloride (PVC) tubes measuring 0.20 m in height and 0.15 m in diameter. The insertion of the columns was performed with the aid of a dump truck's hydraulic system. Upon removal from the field, samples were transported to a greenhouse at Ponta Grossa State University (25°05′25″S, 50°06′12″W).

Two experiments, one with corn in 2008 and another with soybean in 2009, were carried out in a randomized complete block design with a 4×2×2 factorial scheme (lime rate×water level×genotype), and replicated three times. In each experiment, using soil from field plots receiving each lime application rate (0, 4, 8, and 12 Mg ha^{-1}), two water levels were tested based on previous data from Freire (1984): 50 % water filled pore space (WFPS) (water stress) and 80 % WFPS (no water stress). Also, two genotypes of corn (hybrids P 30 F53 and P 32R22) and soybean (cvs. CD 206 and BR 16) were used. To determine the different amounts of water to be applied, the weight of dry and water saturated soil, was measured in order to estimate the WFPS. Corn hybrid P 30 F53 and soybean cv. CD 206 are the same genotypes used in the field experiment; the other two genotypes, corn hybrid P 32R22 (Mazzocato et al. 2002) and soybean cv. BR 16 (Menosso et al. 2000) are known to be sensitive to Al. In our study, two plants of corn or soybean were grown in each column and fertilization was performed with the same amounts of fertilizers used in the field experiment.

The above-ground biomass of both corn and soybean was harvested 40 days after emergence, dried and weighed. Plant tissue contents of N, P, K, Ca, Mg, S, Cu, Zn, and Mn were determined according to the methods described by Malavolta et al. (1997). After plant removal, the PVC tubes were cut at 0–5, 5–10, and 10–20 cm depths. Samples were washed to remove soil and roots were separated. Root length density was determined according to Tennant (1975).

The data from soil columns was submitted to an analysis of variance, using simple regression methods to lime rates, and Tukey test to determine the significance of the effect of water levels and genotypes, with significance at $P=0.05$. Statistical analyses were completed using the SAEG software (Ribeiro Júnior 2001).

Results

Chemical analysis results from the soil samples collected in September 2008, before corn sowing and 52 months after surface liming, showed an increase in pH, Ca and Mg contents, and base saturation with lime application. Also, exchangeable Al saturation and Mn content were reduced to a depth of up to 20 cm (Table 1). On the unlimed plots, the soil showed high acidity, toxic levels of exchangeable Al, high levels of Mn, and low levels of exchangeable Ca and Mg at 0–5, 5–10, and 10–20 cm depths. As a result of the different lime rates applied, plants were exposed to different levels of soil acidity, either in the field or in soil columns.

The different lime rates applied to the soil surface in 2004 resulted in linear increases in leaf contents of P, Ca, and Mg. Similarly, leaf tissue concentrations of Zn and Mn linearly decreased for corn (2008–2009) and soybean (2009–2010) (Table 2).

Corn and soybean grain yields increased with amounts of surface-applied lime, exhibiting a quadractic response (Fig. 2). Based on the regression equations obtained, grain yields in the unlimed plots would be 7,070 kg ha^{-1} of corn and 2,668 kg ha^{-1} of soybean, and the maximum grain yields of corn and soybean would be reached with 9.2 and 10.6 Mg ha^{-1} of lime, respectively. This response resulted in an average yield increase of 42 % in corn and 48 % in soybean.

In the undisturbed soil columns, the root length density of corn (Fig. 3) and soybean (Fig. 4) increased with surface-applied lime rates only under water stress. When water stress was imposed, root length density was greater in corn at 0–5, 5–10, and 10–20 cm depths and in soybean at 5–10 and 10–20 depths, with lime applied to the soil surface. Root growth of the tested corn hybrids and soybean cultivars were similar as compared to lime treatments and water levels in the soil. Only corn hybrid P 32R22 (Al sensitive) had a greater root length density at the soil surface layer (0–5 cm) than corn hybrid P 30 F53 (moderately sensitive to Al) with increasing lime application rates, under water stress.

Nutrient uptake by corn (Table 3) and soybean (Table 4) plants grown in undisturbed soil columns was influenced differently by lime rates, depending on genotype and soil moisture conditions.

In corn hybrid P 32R22 (Al sensitive), increasing lime rates resulted in greater uptake of N, P, K, Ca, Mg, and Zn by plants grown under water stress. However, when plants were grown without water stress, only K and Mg uptake increased (Table 3). In corn hybrid P 30 F53 (moderately sensitive to Al) exposed to water stress, the uptake of K, Ca, Mg, and Zn by plants was greater with increasing lime application rates. However, without water stress only the uptake of Mg increased. Greater rates of surface liming decreased Mn uptake by corn plants at both water stress levels (with or

Table 1 Soil chemical properties for the depths of 0–5, 5–10, and 10–20 cm at 52 months after surface liming

Depth (cm)	Lime (Mg ha^{-1})	pHCaCl$_2$	Al (mmol$_c$ L^{-1})	Mn (mg L^{-1})	Ca (mmol$_c$ L^{-1})	Mg (mmol$_c$ L^{-1})	Base saturation (%)	Al saturation (%)
0–5	0	4.4	11.3	14.5	10.7	6.3	11.2	37.0
	4	5.4	0.7	9.1	34.7	19.7	44.1	1.2
	8	5.9	0.0	8.0	41.0	19.5	57.6	0.0
	12	6.2	0.0	6.5	45.0	26.0	65.0	0.0
	Effect	Q**	Q*	L**	Q**	Q**	Q**	Q**
	CV (%)	2.2	12.4	19.4	18.8	13.8	14.6	20.4
5–10	0	4.2	15.0	7.2	4.0	3.5	4.4	63.3
	4	4.9	2.0	6.6	23.3	12.1	25.9	5.2
	8	5.3	1.3	6.0	27.7	17.7	34.3	2.7
	12	5.7	0.0	5.5	29.3	18.5	42.1	0.0
	Effect	L**	Q**	L*	Q**	Q**	L**	Q**
	CV (%)	3.0	14.9	13.2	17.3	14.5	14.5	10.4
10–20	0	4.3	15.3	5.1	4.3	3.0	4.6	65.4
	4	4.5	9.0	4.1	7,0	8.2	8.1	36.1
	8	4.7	6.7	4.0	13,0	8.0	14.3	23.6
	12	5.0	3.7	3.7	19.0	14.3	23.1	9.8
	Effect	L**	L**	L*	L**	L**	L**	Q**
	CV (%)	3.1	14.3	11.9	20.2	14.2	20.7	12.8

L, linear effect by polynomial regression; Q, quadractic effect by polynomial regression; CV, coefficient of variation; *$P<0.05$; **$P<0.01$

Table 2 Nutrient content in corn and soybean leaves, as affected by surface liming

Lime (Mg ha^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})
Corn (2008–2009)									
0	29.8	1.3	22.5	3.9	1.5	1.1	9.4	20.5	99.0
4	24.2	1.7	24.9	4.1	2.4	1.0	8.3	17.1	88.2
8	25.8	1.7	21.9	4.1	2.9	1.0	8.5	15.7	71.4
12	26.8	2.0	22.7	4.5	3.7	1.0	10.5	15.1	75.9
Effect	ns	L**	ns	L*	L**	ns	ns	L*	L*
CV(%)	8.4	10.9	11.5	15.6	17.9	16.2	11.9	13.1	19.4
Soybean (2009–2010)									
0	37.7	3.7	22.1	6.4	4.0	1.7	25.7	45.8	88.6
4	37.3	3.8	22.1	6.4	4.8	1.6	24.4	38.8	62.0
8	40.2	4.1	30.7	8.2	5.7	1.8	27.7	34.4	60.2
12	39.4	4.4	26.9	7.6	5.8	1.3	25.6	27.5	52.0
Effect	ns	L**	ns	L*	L**	ns	ns	L**	L**
CV(%)	5.8	9.4	10.0	9.6	9.8	15.4	12.4	13.2	7.8

L, linear effect by polynomial regression; Q, quadractic effect by polynomial regression; CV, coefficient of variation; *$P<0.05$; *$P<0.01$. Lime was surface-applied in 2004

without water stress) in hybrid P 32R22 (Al sensitive) but only without water stress in the P 30 F53 hybrid (moderately sensitive to Al).

In soybean cv. BR 16 (Al sensitive) subjected to water stress, greater lime application rates resulted in greater N, K, S, Ca, Mg, and Cu uptake by plants. When the plants were grown without water stress, only N, S, and Mg uptake was greater with increasing lime application rates (Table 4). In soybean cv. CD 206 (moderately sensitive to Al), increasing lime application rates resulted in greater P, S, Ca, Mg, and Cu uptake under water stress. When no water stress was imposed, only Mg uptake was greater. Greater surface lime application rates resulted in lower Mn uptake in both cultivars (BR 16 and CD 206), with or without water stress.

The dry biomass of corn and soybean plants grown in undisturbed soil columns increased with greater rates of surface-applied lime, with and without water stress, exhibiting a quadractic response (Fig. 5). Corn dry biomass production was similar for both hybrids (P 32R22 and P 30 F53) within given lime application rates and water stress levels. In soybean, the increase in dry biomass production with greater lime application rates occurred only in cv. BR 16 (Al sensitive). Water stress affected the growth of corn more than that of soybean, independently of liming and genotype.

When the plants were grown under water stress, soil chemical properties related to soil acidity correlated significantly with dry biomass production of both corn hybrids (Table 5) and soybean cultivars (Table 6), sensitive and moderately sensitive to Al. In soil columns not subjected to water stress, the dry biomass production of only the Al-sensitive soybean genotype (cv. BR 16) showed significant correlation with soil chemical properties related to acidity (Table 6).

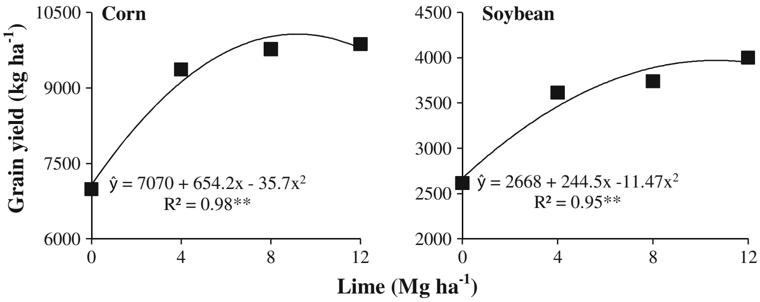

Fig. 2 Grain yield of corn (2008–2009) and soybean (2009–2010) as affected by rates of surface applied lime. **$P<0.01$. Lime was applied in 2004

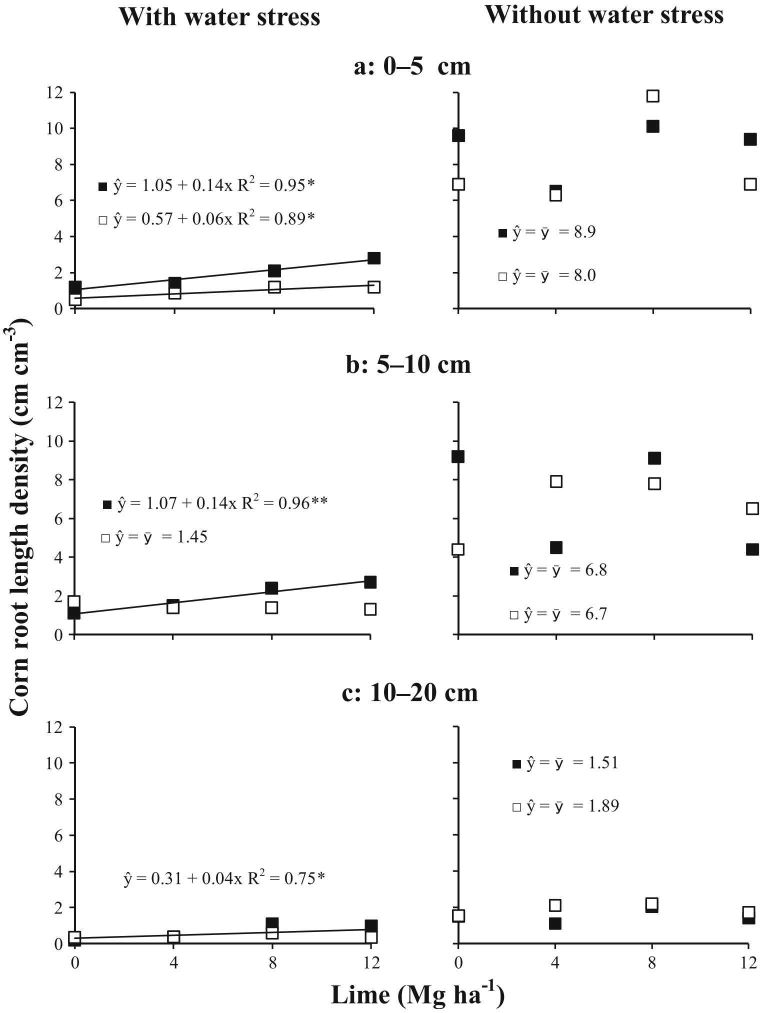

Fig. 3 Root length density of corn hybrids P 32R22 (*closed square*) and P 30 F53 (*open square*) at depths of **a** 0–5 cm, **b** 5–10 cm, and **c** 10–20 cm, as affected by rates of surface applied lime, with and without water stress. $*P<0.05$; $**P<0.01$

Discussion

Surface-applied lime brought about a more marked improvement in acidity of the surface layers of the soil (0–5 and 5–10 cm) than of the 10–20 cm depth (Table 1). The increase in pH with the highest lime application rate (12 Mg ha^{-1}) was 1.8, 1.5, and 0.7 at the 0–5, 5–10, and 10–20 cm depths, respectively. Changes in pH alter the surface chemistry of colloids because of the variable pH nature of the surface charges in Brazilian soils (Van Raij and Peech 1972). Increasing inputs of acids into these soils result in the depletion of basic cations (Ca and Mg) and in the release of exchangeable Al and Mn (Table 1). On the other hand, the elevation in soil pH brought about by liming increases basic cation retention, due to an increase in negative variable electric charges which are generated on the surface of colloids by the dissociation of H$^+$ from hydroxyl groups. Here, greater soil pH resulted in greater base saturation and lower exchangeable Al and Al saturation—in agreement with other results obtained under subtropical no-till cropping systems (Caires et al. 2006; 2008b). Also, higher soil pH brought about by liming resulted in lower available Mn content. Liming acid soils changes the availability of Mn by changing soil solution pH and the form of Mn (Hue et al. 2001). Long-term no-till systems are known to cause nutrient as well as pH stratification, where high pH levels occur in the upper few cm of the soil profile (Caires et al. 2005; Godsey et al. 2007). In order for lime applied on the surface to have an influence on subsoil acidity, alkalinity, usually in the form of HCO_3^- or OH^-, must be transported downwards by mass flow from the surface layers (Sumner 1995). The anions HCO_3^- and OH^-, originating from lime dissolution, react with acidic cations from the soil solution.

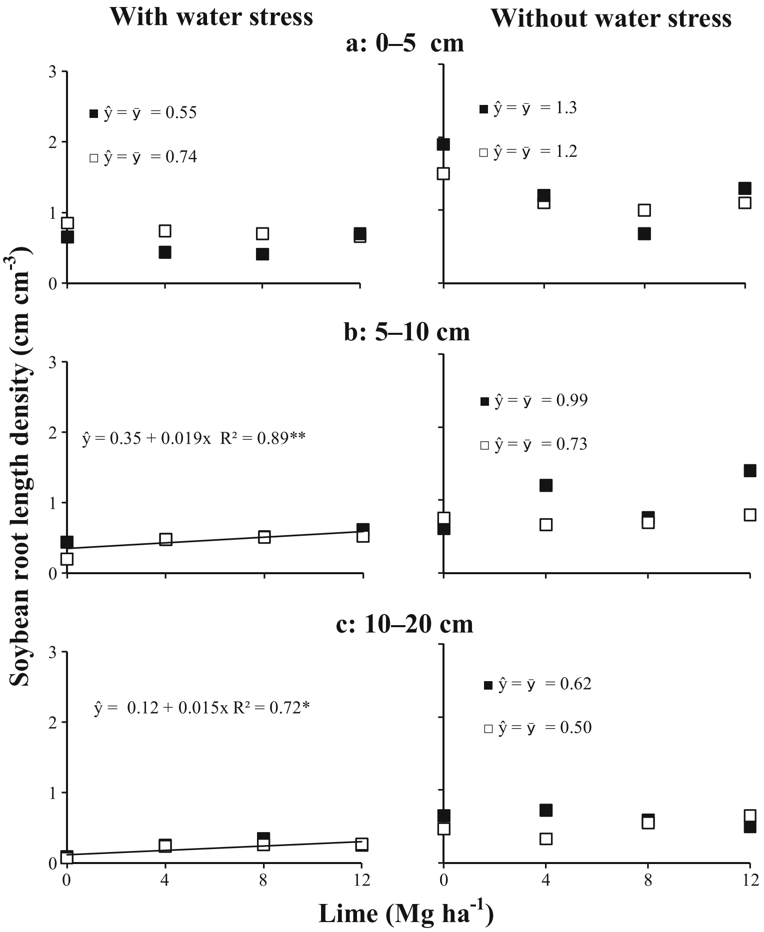

Fig. 4 Root length density of soybean cultivars BR 16 (*closed square*) and CD 206 (*open square*) at depths of **a** 0–5 cm, **b** 5–10 cm, and **c** 10–20 cm, as affected by rates of surface applied lime, with and without water stress. *$P<0.05$; **$P<0.01$

As long as these acidic cations exist, the neutralization of acidity will be limited to the surface layer of the soil, slowing the effect at the subsurface level (Caires et al. 2005). In our study, exchangeable Al levels varied according to lime rates applied and the depth increment. Exchangeable Al contents in the plots not receiving lime were high (> 10 mmol$_c$ L^{-1}) at the 0–5, 5–10, and 10–20 cm depths. Surface liming at 4, 8 or 12 Mg ha^{-1} reduced Al contents to very low levels (≤ 2 mmol$_c$ L^{-1}) in the uppermost layers of the soil (0–5 and 5–10 cm). At the 10–20 cm depth, exchangeable Al level was low only in the plots with surface liming at 12 Mg ha^{-1}.

The greater soil pH and exchangeable Ca and Mg contents resulting from the surface application of lime (Table 1) lead to greater P, Ca, and Mg and lower Zn and Mn concentrations in corn and soybean leaves grown in the field (Table 2). Nutrient uptake by corn (Table 3) and soybean (Table 4) plants grown under water stress in the undisturbed soil columns was strongly influenced by surface liming. Without water stress, nutrient uptake by corn (Table 3) and soybean plants (Table 4) was mostly unchanged after surface liming. Manganese was the only nutrient for which uptake was reduced, in both crops, as a result of surface application of lime in both soil moisture conditions.

Alleviating soil acidity through dolomitic lime application results in greater N, P, S, Mo, Ca, and Mg availability, immobilization of Al and Mn, and reductions in micronutrient availability, including Zn and Cu (Caires 2010). In no-till systems, the available water content in surface layers is high because the soil is covered, which reduces water loss by evaporation (Salton and Mielniczuk 1995; Tarkalson et al. 2006; Moussa-Machraoui et al. 2010). The greater available moisture in the soil surface layer improves nutrient transport and absorption processes (Caires and Da Fonseca 2000) and explains the responses observed here with corn

Table 3 Nutrient uptake by corn hybrids grown in soil columns ($\hat{y}$) as a function of surface liming rates application (x, in Mg ha^{-1}), with and without water stress

$\hat{y}$	Water stress	Corn hybrid	Equation	R²
N (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = 16.6 + 6.5x - 0.44x^2$	0.88*
		P 30 F53	$\hat{y} = \bar{y} = 36.9$	—
	Without	P 32R22	$\hat{y} = \bar{y} = 263.6$	—
		P 30 F53	$\hat{y} = \bar{y} = 304.1$	—
P (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = 1.2 + 0.67x - 0.05x^2$	0.94**
		P 30 F53	$\hat{y} = \bar{y} = 2.25$	—
	Without	P 32R22	$\hat{y} = \bar{y} = 26.6$	—
		P 30 F53	$\hat{y} = \bar{y} = 22.6$	—
K (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = 21.4 + 12.9x - 0.89x^2$	0.90**
		P 30 F53	$\hat{y} = 17.9 + 4.4x - 0.27x^2$	0.94*
	Without	P 32R22	$\hat{y} = 386.4 + 61.7x - 4.4x^2$	0.84*
		P 30 F53	$\hat{y} = \bar{y} = 322.1$	—
Ca (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = 2.3 + 0.17x$	0.66*
		P 30 F53	$\hat{y} = 1.75 + 0.9x - 0.06x^2$	0.99**
	Without	P 32R22	$\hat{y} = \bar{y} = 33.9$	—
		P 30 F53	$\hat{y} = \bar{y} = 41.6$	—
Mg (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = 1.48 + 0.25x$	0.78**
		P 30 F53	$\hat{y} = 1.8 + 0.26x$	0.72**
	Without	P 32R22	$\hat{y} = 25.3 + 1.3x$	0.74*
		P 30 F53	$\hat{y} = 21.2 + 2.8x$	0.75*
S (mg $plant^{-1}$)	With	P 32R22	$\hat{y} = \bar{y} = 0.78$	—
		P 30 F53	$\hat{y} = \bar{y} = 0.46$	—
	Without	P 32R22	$\hat{y} = \bar{y} = 8.2$	—
		P 30 F53	$\hat{y} = \bar{y} = 6.5$	—
Cu (μg $plant^{-1}$)	With	P 32R22	$\hat{y} = \bar{y} = 7.07$	—
		P 30 F53	$\hat{y} = \bar{y} = 8.09$	—
	Without	P 32R22	$\hat{y} = \bar{y} = 48.8$	—
		P 30 F53	$\hat{y} = \bar{y} = 58.5$	—
Zn (μg $plant^{-1}$)	With	P 32R22	$\hat{y} = 17.9 + 6.3x - 0.45x^2$	0.99**
		P 30 F53	$\hat{y} = 23.5 + 6.5x - 0.44x^2$	0.91**
	Without	P 32R22	$\hat{y} = \bar{y} = 183.9$	—
		P 30 F53	$\hat{y} = \bar{y} = 186.7$	—
Mn (μg $plant^{-1}$)	With	P 32R22	$\hat{y} = \bar{y} = 102.1 - 4.59x$	0.93**
		P 30 F53	$\hat{y} = \bar{y} = 79.29$	—
	Without	P 32R22	$\hat{y} = 1147.7 - 82.2x$	0.84**
		P 30 F53	$\hat{y} = 1395.6 - 104.02x$	0.81**

R^2, coefficient of determination; *$P<0.05$; **$P<0.01$

(Table 3) and soybean (Table 4) nutrition after surface application of lime. Such responses were more pronounced under water stress than without water stress or at field conditions (Table 2), confirming the hypothesis that the effects of soil acidity reduction by surface liming on no-till corn and soybean nutrition are more important under water stress.

The greater availability of N with liming is due to the favourable effect of a higher pH on soil organic matter mineralization (Caires 2010). It is know that

Table 4 Nutrient uptake by soybean cultivars grown in soil columns ($\hat{y}$) as a function of surface liming rates application (x, in Mg ha^{-1}), with and without water stress

$\hat{y}$	Water stress	Soybean cultivar	Equation	R^2
N (mg $plant^{-1}$)	With	BR 16	$\hat{y} = 31.1 + 2.69x - 0.21x^2$	0.95**
		CD 206	$\hat{y} = \bar{y} = 36.1$	—
	Without	BR 16	$\hat{y} = 41.3 + 2.1x$	0.83**
		CD 206	$\hat{y} = \bar{y} = 44.2$	—
P (mg $plant^{-1}$)	With	BR 16	$\hat{y} = \bar{y} = 8.2$	—
		CD 206	$\hat{y} = 5.5 + 0.22x$	0.64*
	Without	BR 16	$\hat{y} = \bar{y} = 11.6$	—
		CD 206	$\hat{y} = \bar{y} = 9.7$	—
K (mg $plant^{-1}$)	With	BR 16	$\hat{y} = 22.3 + 1.8x - 0.15x^2$	0.68*
		CD 206	$\hat{y} = \bar{y} = 24.3$	—
	Without	BR 16	$\hat{y} = \bar{y} = 37.1$	—
		CD 206	$\hat{y} = \bar{y} = 29.9$	—
Ca (mg $plant^{-1}$)	With	BR 16	$\hat{y} = 7.9 + 1.8x - 0.13x^2$	0.96**
		CD 206	$\hat{y} = 5.6 + 1.49x - 0.10x^2$	0.89**
	Without	BR 16	$\hat{y} = \bar{y} = 18.7$	—
		CD 206	$\hat{y} = \bar{y} = 13.6$	—
Mg (mg $plant^{-1}$)	With	BR 16	$\hat{y} = 3.07 + 0.99x - 0.07x^2$	0.95**
		CD 206	$\hat{y} = 2.63 + 0.94x - 0.07x^2$	0.99**
	Without	BR 16	$\hat{y} = 5.3 + 0.28x$	0.78**
		CD 206	$\hat{y} = 5.2 + 0.16x$	0.90*
S (mg $plant^{-1}$)	With	BR 16	$\hat{y} = 1.5 + 0.10x - 0.008x^2$	0.77**
		CD 206	$\hat{y} = 1.2 + 0.04x$	0.93**
	Without	BR 16	$\hat{y} = 1.5 + 0.08x$	0.89**
		CD 206	$\hat{y} = \bar{y} = 1.68$	—
Cu (μg $plant^{-1}$)	With	BR 16	$\hat{y} = 6.4 + 0.42x - 0.03x^2$	0.66*
		CD 206	$\hat{y} = 4.5 + 0.79x - 0.05x^2$	0.88**
	Without	BR 16	$\hat{y} = \bar{y} = 6.2$	—
		CD 206	$\hat{y} = \bar{y} = 5.85$	—
Zn (μg $plant^{-1}$)	With	BR 16	$\hat{y} = \bar{y} = 28.1$	—
		CD 206	$\hat{y} = \bar{y} = 33.6$	—
	Without	BR 16	$\hat{y} = \bar{y} = 19.3$	—
		CD 206	$\hat{y} = \bar{y} = 17.2$	—
Mn (μg $plant^{-1}$)	With	BR 16	$\hat{y} = 148.1 - 10.1x$	0.80**
		CD 206	$\hat{y} = 103.9 - 5.13x$	0.99**
	Without	BR 16	$\hat{y} = 122.9 - 8.3x$	0.78*
		CD 206	$\hat{y} = 144.7 - 10.9x$	0.75*

R^2, coefficient of determination; *$P<0.05$; **$P<0.01$

water controls microbial activity in the soil and thus determines rates of mineralization (Stark and Firestone 1995; Sleutel et al. 2008). Linn and Doran (1984) showed that %WFPS was a very useful indicator of microbial activity, and that maximum aerobic activity occurred at 60 % WFPS across a wide range of soils. In other studies, the optimum %WFPS for N mineralization was 56 % in a soil incubated with addition of crop residues (De Neve and Hofman 2002) and ranged between 57 % and 78 % in undisturbed soil cores (Sleutel et al. 2008). In our study, an increase in N uptake by corn (Table 3) and soybean (Table 4) with

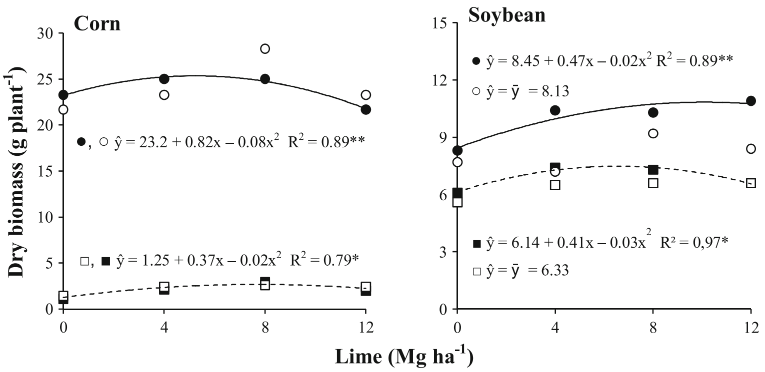

Fig. 5 Dry biomass of corn and soybean, as affected by rates of surface applied lime, with and without water stress, and different hybrids/cultivars: with water stress – corn P 32R22/soybean BR 16 (*closed square*), corn P 30 F53/soybean CD 206 (*open square*); without water stress – corn P 32R22/soybean BR 16 (*closed circle*), corn P 30 F53/soybean CD 206 (*open circle*). *$P<0.05$; **$P<0.01$

surface application of lime was only observed in Al-sensitive genotypes (hybrid corn P 32R22 and soybean cv. BR 16) under water stress (50 % WFPS). Thus, N uptake in both crops must have been affected by the limitation on root growth resulting from by high soil acidity under water stress. In addition, greater Mo availability resulting from the rise in soil pH with liming may have improved biological N_2 fixation in soybean grown under water stress.

Greater soil availability of P and S with liming occurs because phosphate and sulphate ions which are adsorbed onto oxy-hydroxides of Fe and Al are

Table 5 Linear correlation coefficients between chemical properties related to soil acidity and dry biomass production of corn hybrids grown in soil columns, with and without water stress, for different depths

Propertie	Depth	With water stress		Without water stress	
		P 32R22	P 30F53	P 32R22	P 30F53
pHCaCl$_2$	0–5 cm	0.60**	0.47*	0.37	0.32
	5–10 cm	0.54*	0.44*	0.09	0.26
	10–20 cm	0.40*	0.36	0.17	0.26
Exchangeable Al (mmol$_c$ L^{-1})	0–5 cm	−0.67**	−0.50*	−0.05	−0.12
	5–10 cm	−0.65**	−0.50*	−0.07	0.20
	10–20 cm	−0.55*	−0.48*	0.08	−0.15
Exchangeable Ca (mmol$_c$ L^{-1})	0–5 cm	0.64**	0.49*	0.10	0.14
	5–10 cm	0.66**	0.50*	0.01	0.04
	10–20 cm	0.42*	0.35	0.07	0.08
Exchangeable Mg (mmol$_c$ L^{-1})	0–5 cm	0.52*	0.45*	0.21	0.28
	5–10 cm	0.65**	0.48*	0.22	0.18
	10–20 cm	0.33	0.36	0.16	0.12
Al saturation (%)	0–5 cm	−0.67**	−0.51*	−0.15	−0.24
	5–10 cm	−0.66**	−0.51*	−0.13	−0.14
	10–20 cm	−0.56*	−0.45*	−0.07	−0.16
Base saturation (%)	0–5 cm	0.62**	0.48*	0.13	0.22
	5–10 cm	0.59**	0.46*	0.26	0.29
	10–20 cm	0.45*	0.32	0.19	0.23

*$P<0.05$; **$P<0.01$

Table 6 Linear correlation coefficients between chemical properties related to soil acidity and dry biomass production of soybean cultivars grown in soil columns, with and without water stress, for different depths

Propertie	Depth	With water stress		Without water stress	
		BR 16	CD 206	BR 16	CD 206
$pHCaCl_2$	0–5 cm	0.45*	0.72**	0.56*	0.37
	5–10 cm	0.39*	0.69**	0.55*	0.35
	10–20 cm	0.38*	0.60**	0.38	0.30
Exchangeable Al ($mmol_c\ L^{-1}$)	0–5 cm	−0.67**	−0.76**	−0.59*	−0.24
	5–10 cm	−0.62**	−0.75**	−0.59*	−0.24
	10–20 cm	−0.48*	−0.71**	−0.57*	−0.34
Exchangeable Ca ($mmol_c\ L^{-1}$)	0–5 cm	0.54*	0.74**	0.58*	0.32
	5–10 cm	0.59**	0.75**	0.58*	0.31
	10–20 cm	0.51*	0.56*	0.46	0.32
Exchangeable Mg ($mmol_c\ L^{-1}$)	0–5 cm	0.58**	0.72**	0.58*	0.22
	5–10 cm	0.49*	0.71**	0.55*	0.31
	10–20 cm	0.38	0.62**	0.25	0.28
Al saturation (%)	0–5 cm	−0.68**	−0.76**	−0.58*	−0.22
	5–10 cm	−0.65**	−0.76**	−0.56*	−0.23
	10–20 cm	−0.39	−0.71**	−0.56*	−0.35
Base saturation (%)	0–5 cm	0.49*	0.73**	0.57*	0.36
	5–10 cm	0.52*	0.72**	0.56*	0.35
	10–20 cm	0.29	0.55*	0.40	0.39

*$P<0.05$; **$P<0.01$.

released when soil pH increases (Caires 2010). In the case of P uptake, it is also important to consider that aside from access to more soluble forms of P in soils with lower acidity, plants are able to exploit a larger volume of soil. This explains why liming increased P concentration in corn and soybean leaves in the field experiment (Table 2) and also, depending on the genotype, P uptake by corn (Table 3) and P and S uptake by soybean (Table 4) grown under water stress in undisturbed soil columns.

With increasing rates of surface applied lime, the greater Ca and Mg concentrations in corn and soybean leaves grown in the field (Table 2) and the greater Ca and Mg uptake by corn (Table 3) and soybean (Table 4) grown in undisturbed soil columns resulted from greater exchangeable Ca and Mg contents (Table 1). The greater uptake of K by corn plants grown under water stress with liming (Table 3) may be related to greater amounts of soil exchangeable Ca, resulting from the release of K from exchange sites into the soil solution (Nogueira and Mozeto 1990).

The lower Zn and Mn concentrations in corn and soybean leaves grown in the field (Table 2) and in Mn uptake by corn (Table 3) and soybean (Table 4) grown in the undisturbed soil columns must have occurred mainly because of the immobilization of these nutrients with increasing soil pH. Caires et al. (2009) found that surface-applied lime in a subtropical long-term no-till cropping system promoted a decrease in Zn concentrations of crops tissues because of a rise in soil pH in the surface layers. The lower Zn uptake by plants can also be explained by a rise in P absorption due to the competitive inhibition that occurs between these nutrients in the plant (Marschner 1995). The reduction in plant Mn uptake with lime application has been related to a rise in soil pH (Caires and Da Fonseca 2000) and in exchangeable Ca and Mg contents (Ritchey et al. 1982). Liming reduces Mn availability in soil to non-toxic levels (Quaggio et al. 1982), but at excessive rates, it may cause Mn deficiency in the plant (Tanaka et al. 1992). In our study, although liming reduced Mn uptake, corn and soybean plants did not show toxicity symptoms or Mn deficiency.

Even though Zn (Caires and Da Fonseca 2000; Caires et al. 2009) and Cu (Harmsen and Vlek 1985) availability is reduced with a rise in soil pH, liming resulted in greater Zn uptake in corn (Table 3) and Cu uptake in soybean (Table 4) when these were grown under water stress. This is likely explained by the gain in dry above-ground biomass production with lime application (Fig. 5). Because these effects were not observed with Mn uptake, we conclude that liming affects the availability in soil and uptake by plants of Mn more than Zn and Cu.

The positive responses observed in corn and soybean grain yields as a result of the increasing rates of surface-applied lime (Fig. 2) were more pronounced than those commonly found in the literature. High grain yields in corn and soybean have been obtained on acidic Brazilian soils under no-till (Caires et al. 2005; 2006), and surface-applied lime has also been observed to have no effect on grain yield in other studies conducted under diverse soil and climatic conditions (Godsey et al. 2007; Brown et al. 2008). The factors explaining high crop yields in acid soils under no-till systems include the following: (i) lower phytotoxicity of Al for the plants (Brown et al. 2008; Vieira et al. 2008; Alleoni et al. 2010), (ii) sufficient concentrations of exchangeable cations (Caires et al. 1998; 2006), and (iii) higher available moisture in the soil (Salton and Mielniczuk 1995; Tarkalson et al. 2006; Moussa-Machraoui et al. 2010). In our study, a lower rainfall rate occurred only for a short period at the beginning of corn growing season in 2008, and rainfall was never limiting during the soybean growing season in 2009–2010 (Fig. 1). However, greater soil acidity with more exchangeable Al and less exchangeable bases in the unlimed control plots severely compromised corn and soybean grain yields. In another trial conducted in southern Brazil, on a no-till acid soil with toxic level of exchangeable Al (8.5 $\text{mmol}_c\ \text{L}^{-1}$) and low level of exchangeable Mg (6.6 $\text{mmol}_c\ \text{L}^{-1}$), Oliveira and Pavan (1996) found an increase in soybean grain yield of 42 % with surface application of dolomitic lime. In our study, surface liming resulted in an average yield increase of 42 % in corn and 48 % in soybean (Fig. 2). On the unlimed plots, the soil had low levels of exchangeable Mg at the 0–5, 5–10, and 10–20 cm depths (Table 1). In addition, the Mg content in corn and soybean leaves (Table 2) and uptake of Mg by corn (Table 3) and soybean (Table 4) plants were always higher with surface-applied dolomitic lime rates, even when plants were grown in undisturbed soil columns without water stress. Thus, the increased soil availability of exchangeable Mg with liming may have caused a greater influence on crop yield response in our study.

We hypothesized that corn and soybean plants exposed to drought stress under no-till systems are more affected by Al toxicity, and that the effects of soil acidity reduction by surface liming on no-till corn and soybean root growth are greater when water in the topsoil is depleted. In fact, soil acidity, when associated with water deficit, severely affected root length density of corn (Fig. 3) and soybean (Fig. 4), and the alleviation of acidity by surface application of lime was essential to improve root growth under water stress. However, root length density of corn and soybean under water stress was lower than without water stress, even when soil acidity was reduced with lime application. Root elongation in drying soil is generally limited by a combination of mechanical impedance and water stress, and there is a strong interplay between soil strength and water content (Bengough et al. 2011). Thus, it is likely that in our study soil strength increased as a result of the water stress conditions, and restricted crop root growth. The lack of response to liming in root length density in corn (Fig. 3) and soybean (Fig. 4) in the absence of water stress shows that acidity levels and exchangeable Al were not limiting root growth, when adequate amounts of water were available in the soil. The high organic matter content in no-till soils (Bayer et al. 2000; Rhoton 2000) may buffer against Al phytotoxicity (Brown et al. 2008; Vieira et al. 2008). Since the formation of Al-organic complexes reduces Al toxicity (Diatloff et al. 1998; Alleoni et al. 2010), corn and soybean root growth was not found to be affected by Al concentration in soil solution, in a no-till system under plentiful, well-distributed rainfall (Caires et al. 2008b). However, in unfavorable rainfall conditions, the toxicity of Al severely compromised crop root growth and yield under no-till (Caires et al. 2008a). In a study concerning exchangeable elements in soil solution under water stress, it was observed that as the water content in soil decreased, there was a greater release of cations of higher valency into the soil solution (Dyers et al. 2008). Moreover, a fraction of Al is complexed with high molecular weight organic compounds (Alleoni et al. 2010) and can be easily solubilised in low-moisture soil conditions (Christ and David 1996).

It should also be noted that an increase in ionic strength in soil solution due to a soil water deficit may result in higher Al activity (Vieira et al. 2008).

Increasing rates of surface liming lead to greater dry biomass production in corn and soybean, at both levels of soil moisture (with or without water stress). Because there was no effect of liming on root growth of corn (Fig. 3) and soybean (Fig. 4) grown without water stress, but there was an effect on shoot dry matter, the 40 day growth period was likely sufficient for plants grown without water stress to fully exploit the volume of the cores, regardless of liming. Indeed, the dry biomass production in corn and soybean genotypes was more affected by water stress than by soil acidity (Fig. 5). Regardless of liming, corn plants were much more sensitive to water stress than soybean plants. The average amount of dry corn biomass was reduced from 23.6 g plant^{-1} without water stress to 2.3 g plant^{-1} under water stress, a reduction of 90 %. In soybean plants, the reduction in dry biomass production due to water stress was only 27 % (from 9.1 g plant^{-1} without water stress to 6.6 g plant^{-1} under water stress). In both corn hybrids, chemical properties related to soil acidity were closely related to dry biomass production only when plants were grown under water stress (Table 5). In soybean, alleviating soil acidity through lime application improved the production of dry biomass in both cultivars BR 16 (Al sensitive) and CD 206 (moderately sensitive to Al), when plants were grown under water stress. These results confirm the hypothesis that the effects of soil acidity reduction by surface liming on growth of corn and soybean under no-till are more important under water stress. However, when no water stress was imposed, liming also lead to greater dry biomass in soybean cv. BR 16 (Al sensitive). Therefore, despite Al toxicity being higher in a no-till system under water stress, soil acidity may compromise growth in a highly Al-sensitive genotype, even though water availability is adequate.

Conclusions

Surface application of lime under no-till improved root growth and plant nutrition, and increased grain yields of corn and soybean. The reduction in soil acidity brought about by surface liming, and ameliorating effects on root growth and nutrition of corn and soybean were more important when water in the topsoil was depleted. Because of Al complexation with organic matter, Al toxicity was low when corn and soybean were grown without water stress. However, when water stress was imposed, Al toxicity severely compromised root growth and plant nutrition. Corn genotypes were more affected by water stress than soybean genotypes. Because Al toxicity is greater during drought periods and also because the development of highly Al sensitive genotypes is compromised by soil acidity, even with adequate soil moisture, surface application of lime is an effective and important practice to maximize crop grain yields under no-till systems.

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